Theoretical and Experimental Investigation of Efficient Photonic Crystal Cavity-Waveguide Couplers

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Abstract: Coupling of photonic crystal (PC) linear three-hole defect cavities to PC waveguides is theoretically and experimentally investigated. An improved coupling is obtained by tilting the cavity axis by 60^o with respect to the waveguide direction.

Structures that consist of InGaAs/GaAs quantum dots (QDs) coupled to two-dimensional photonic crystal cavities (PCC) are promising candidates for highly efficient single photon sources (SPS). They represent essential devices for quantum cryptography and quantum computation. In order to efficiently implement quantum computation devices one would need to integrate photonic circuits directly on the chip. These circuits consist of SPSs that inject single photons into the waveguides, which redirects them to other quantum nodes, i.e. other PC cavities containing QDs. Once the necessary quantum operations have been performed, photons need to be outcoupled from the waveguide either out of PC plane for vertical collection (e.g. by coupling the photons back into an "output cavity" that scatters them out of plane), or collected in PC plane (e.g. by outcoupling to a fiber) The performance of this kind of circuit is limited by the coupling efficiency between the cavities and the waveguides. Our work investigates this coupling with the goal of improving the efficiency of single photon transmission from one cavity to another.

To get efficient coupling, the modes of the cavity and the waveguide need to be spatially overlapped and frequency matched [1]. Photonic crystals exhibit three types of loss mechanisms: in-plane loss, out-of-plane loss, and loss due to imperfections in fabrication and absorption inside the material. These loss mechanisms are considered independent and a quality factor is associated with each one of them: $Q_{\parallel}$ for in-plane, $Q_{\perp}$ for out-of-plane and Q_{other} for material loss and fabrication imperfections. The total quality factor of the system is given by the formula [2]:

$$\frac{1}{Q_{tot}} = \frac{1}{Q_{\parallel}} + \frac{1}{Q_{\perp}} + \frac{1}{Q_{other}} = \frac{1}{Q_{\parallel}} + \frac{1}{Q_c} \qquad (1)$$

For a good single photon transfer, the in-plane coupling into the waveguide modes needs to be dominant so $Q_{\parallel}$ should be lower than Q_c. On the other hand, good single photon sources require cavities with a quality factor higher than $\sim 10^3$ which implies $Q_{\parallel} > 10^3$. For other applications single photons need to be scattered out of plane from a PC waveguide through an output cavity. In order to achieve high transfer efficiency from waveguides to the output cavities, the cavity-waveguide system needs to be in the critical coupling regime defined by $Q_{\parallel} = Q_{\perp}$. In that case, the output cavity does not need to be one with a very high quality factor.

We have previously fabricated single photon sources based on single and three hole defect (L3) PCCs with quality factors $Q_c \sim 5000$ [3]. Therefore, for a considerable fraction of the power to be dissipated in the waveguide, $Q_{\parallel} \sim 5000$ is needed. The evanescent tail of the L3 cavity field is mainly concentrated along directions inclined by $\pi/6$ with respect to the cavity axis [Fig.1]. This can be explained by the anti-symmetry of the mode along the cavity axis and the high effectiveness of the PC mirrors along 0 and $\pi/3$ directions. Because of the periodic structure of the PC, waveguides can be brought near the cavity only along the 0 and $\pi/3$ directions. Since the 0 direction overlaps the low-filed intensity region, we choose to draw the waveguide along the $\pi/3$ direction (as opposed to the standard approach, where the waveguide axis is aligned with that of the cavity mode).

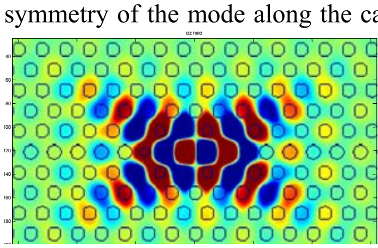
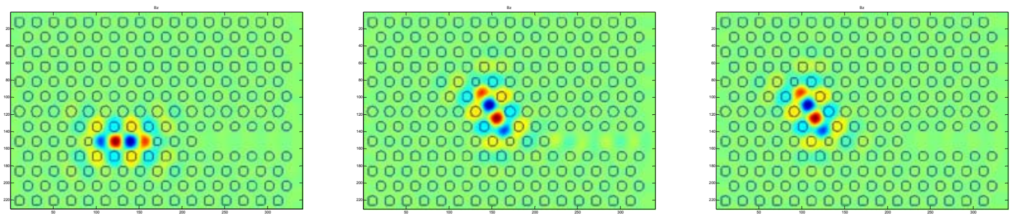


Fig.1 Magnetic field for an odd-even (in the x-y directions [2]) mode of the L3 cavity

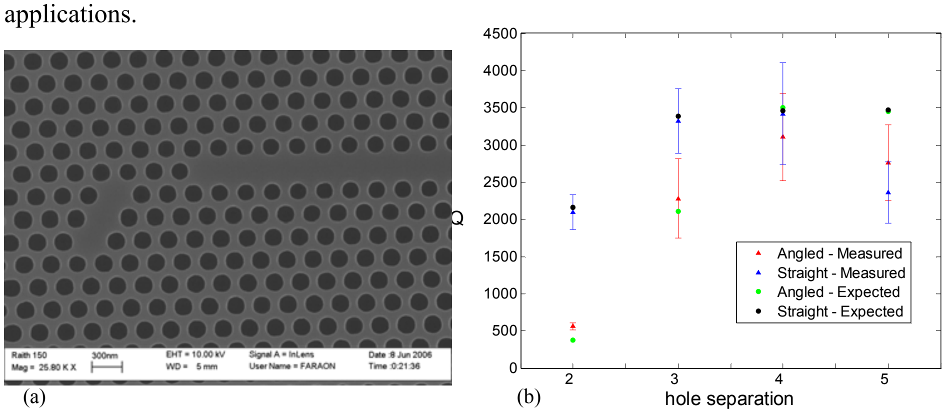
Three dimensional finite difference time domain simulations have been performed to determine the quality factor associated with the coupling of the L3 cavity to the waveguide. Two distinct configurations have been tested (Fig.2), named “angled” and “straight”. In the straight configuration, the waveguide is butt-coupled along the cavity axis while in the angled configuration the direction of the waveguide makes a $\pi/3$ angle with the cavity axis. The number of PC holes that separate the cavity from the waveguide was varied thus changing the coupling.



(a) (b) (c)

Fig.2 Images of simulated structures. (a) straight configuration with three hole separation. (b) angled configuration with three hole separation. (c) angled, five hole separation.

The simulated structures where then fabricated (Fig.3) on a GaAs substrate with InGaAs quantum dots (QDs) that act as an internal light source. We made structures with two, three and four holes separation. The sample was cooled to 5K and a Ti:Sapphire laser was used to excite the QDs. The quality factor was measured for each configuration. The experimental values were compared to expected results from simulations and a good agreement was observed (Fig.3). The dropping efficiency into the waveguide changes from ~80% in the case of the angled configuration with 2 hole separation down to zero for four and five hole separation. However, even though good coupling is obtained, the total quality factor of the cavity gets degraded. The design should be optimized to obtain coupling parameters suitable for particular applications.



(a) (b)

Fig.3 (a) Fabricated structure. (b) Measured quality factor versus the results expected from simulations. The errors are dominated by fluctuations of the parameters due to fabrication. The discrepancy for 2-hole separation results from the overestimation of $Q_\perp$ used in the fit.

In conclusion, we investigated PC cavity waveguide couplers both by simulation and experiments thus proving that we can have a good control of the coupling parameters. Coupling efficiency as high as ~80% was obtained for specially designed fabricated structures.

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References

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